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16. ABSTRACT The paper discusses laboratory tests of a modified, popular dual-chamber woodstove to determine its ability to reduce emissions. In dual-chamber stoves, the primary chamber is for fuel volatilization, and the secondary is for combustion. The original stove was first operated at low, medium, and high burn rates to establish baseline performance. The stove was then modified to include an electrical igniter and a controlled flow of air to the secondary chamber and was tested again under the same conditions. Variables measured included gas stream temperatures upstream and downstream of the secondary chamber (which indicate secondary combustion) and exhaust stream concentrations of carbon monoxide and unburned hydrocarbons (which indicate emissions). The paper discusses the effectiveness of these modifications in sustaining secondary combustion and reducing emissions.

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SECONDARY COMBUSTION IN A DUAL-CHAMBER WOODSTOVE

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ABSTRACT

Many woodstove design modifications have been evaluated for their ability to reduce emissions. One of the concepts employed is the use of dual chambers, a primary chamber for volatilization and a secondary chamber for combustion. Commonly, combustion air is naturally aspirated into the secondary combustion chamber. In this study, a popular dual-chamber woodstove with modifications was laboratory tested. The original appliance was first burned at low, medium, and high burn rates to establish baseline performance. The stove was then modified to include an electric ignitor and a controlled flow of air to the secondary chamber and was tested again under the same conditions. Variables measured include the gas stream temperatures upstream and downstream of the secondary chamber, which indicate secondary combustion, and exhaust stream concentrations of carbon monoxide (CO) and unburned hydrocarbons (HC), as indicators of emissions. This paper discusses the effectiveness of these woodstove modifications at sustaining secondary combustion and reducing emissions.

INTRODUCTION

The increased use of wood as a fuel for residential heating has simultaneously reduced the demand on fossil fuel supplies and increased air pollution; the magnitude of the air pollution problem is well documented (Hartman and Rives 1985). The airtight woodstoves in wide use today regulate heat output by throttling the air supply to the combustion chamber, producing fuel-rich conditions that usually allow the exhaust of unburned combustibles. More complete combustion is the design objective for new woodstoves, and many design alternatives have been evaluated. One of the most promising design concepts is the use of dual chambers within the woodstove. One chamber, the primary chamber, contains the burning wood and allows limited air entry to sustain a smoldering fire that volatilizes the combustibles. The combustible gases then pass to the secondary chamber, where the combustion is completed with the aid of additional air. The advantage to this arrangement is that the rate of volatilization can be decoupled from the combustion process so that complete combustion can be achieved at low burn rates.

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Sustaining secondary combustion in a woodstove can be difficult. As with all combustion, the combustibles and the air must be well mixed, the composition must be within the flammability limits, and the temperature must be greater than the ignition temperature. In a woodstove, the rate at which the combustibles are volatilized changes throughout the burn cycle. The flow rate of secondary air, which is usually naturally aspirated, changes with the primary flow, as does the turbulence which causes mixing. The temperature in the secondary chamber changes as well. Stove design modifications that control these widely varying conditions can promote secondary combustion. These design factors include methods to sustain high temperature in the secondary chamber, preheat the supply air to the secondary chamber, regulate the gaseous composition, and use an ignition source in the secondary chamber (Allen and Cooke 1981). The first three of these concepts have been tested in the laboratory to measure their effectiveness in reducing emissions (Allen and Piispanen 1984; Knight and Knight 1983). In general, the emissions were somewhat reduced when the stove was burned at medium and high firing rates, but little or no emission reduction was observed at the low burn rates that are commonly used in homes.

The use of an ignition source to sustain the secondary combustion has received limited testing. A small pilot flame using natural gas or an electrical glow plug could provide the local heating necessary to ignite the gaseous mixture in the secondary chamber. While theoretically appealing, this concept faces practical problems associated with supplying an external energy source to a woodstove. Prior to addressing that practicality, it is necessary to document the effectiveness of an ignition source at sustaining secondary combustion and to measure the concomitant emission reduction. This paper presents the preliminary results of an experimental study that measured the performance of an ignition source in a dual-chamber woodstove.

PROCEDURE

This study was based on the performance of a commercially available dual-chamber woodstove. This stove, shown schematically in Figure 1, utilizes the S-flow configuration to promote secondary combustion. During operation, the wood pieces are loaded into the primary chamber. A small fire burns in the primary chamber to heat the wood and volatilize the combustibles; the release rate is controlled by the amount of primary air introduced through a damper. The gaseous combustible products then pass through a narrow throat into the secondary chamber. Secondary air is introduced at the throat. Secondary combustion, if any, occurs in the secondary chamber, which is lined with firebrick to minimize cooling of the gases. The combustion products then pass beneath the top of the stove to transfer heat prior to exhaust.

The basic stove was modified in two ways: (1) The secondary air supply was connected to a compressed air system, with an in-line rotameter, to regulate the flow rate. (2) An electric glow plug was installed near the entrance to the secondary chamber. The glow plug, similar to those used as ignitors in gas appliances, had a flat blade shape 0.5x2.0 in (1.27x5.08 cm) that protrudes into the gas stream. This ignitor draws 3.5 amps from 120 VAC supply. Both of these modifications were left in place, even when not in use during testing, to provide the same gas flow geometry within the stove.

The woodstove was installed and operated in an air-conditioned laboratory. The stove was mounted on a platform scale for monitoring the wood consumption rate. The exhaust pipe included an oil seal joint to "float" the stove from the building exhaust system.

The stove was instrumented to monitor performance and emissions. Two thermocouples with aspirated shields were mounted in the gas stream passages, one upstream and another downstream of the secondary chamber. The rates of emission of carbon monoxide (CO) and unburned hydrocarbons (HC) were continuously monitored by drawing samples at an elevation of 5 feet (1.5 m) above the stove top. The CO was measured with a nondispersive infrared sensor and the HC was measured with a flame ionization detector, supplied by a non-condensing heated line. All data were recorded with a microcomputer-based data acquisition system that multiplexed all sensors at one minute intervals.

During testing, white oak cordwood was burned. Wood pieces were typically 12-14 in (30-35 cm) long with hydraulic diameter of about 2 in (5cm). The wood moisture content was estimated to be 12-15%, but was not measured; moisture content was held constant by storing the wood in a controlled environemt room. A typical test charge consisted of two to three pieces of wood weighing 7-8 pounds (3-4 kg). The wood was placed on a bed of coals comprising about 1-1.5 pounds (0.5-1 kg) of the previous charge, so about 5-7 pounds (2-3 kg) of wood were burned during each cycle. For the duration of the burn cycle, the damper controlling the flow of primary air remained stationary. The burn cycle was deemed complete when the firebox temperature returned to within about 25 F (14 C) of the starting temperature. Since testing concentrated on the first portion of the burn when volatile hydrocarbons dominate the fuel supply, the exact definition of the completion of the burn cycle was not critical. Rather, emphasis was placed on maintaining consistency of the beginning of each cycle. At the completion of each burn cycle, the gas sampling tubes were flushed and the samplers were recalibrated.

The stove was tested with three combinations of modifications: original design, active ignitor with naturally aspirated secondary air supply, and active ignitor with regulated secondary air supply. The stove was burned with three primary air settings: low fire with the damper at one-fourth open, medium fire at one-half open, and high fire at wide open. At each condition, the burn cycle was repeated several times. Table 1 lists the test conditions and the number of replications at each.

The stove was operated at constant conditions throughout a burn cycle. When the ignitor was used, it was turned on prior to the beginning of the burn cycle. When the regulated flow of secondary combustion air was added to the test, that flow was activated prior to the start of the burn and continued for the duration of the burn. The flow rate was about 100 SCFH (standard cubic feet per hour).

RESULTS

For the purposes of this study, all emission results were recorded in those units utilized by the gas samplers, which are concentration levels in parts per million (ppm) or percent concentration. This approach provides an adequate format for comparing the various configurations, even if it does differ from the units used more commonly for woodstove emissions, such as grams per kilogram of wood burned or grams per hour.

The temperatures and emission rates of CO and HC were recorded

continuously for each of the burns performed in this study; typical burn cycle histories are plotted in Figure 2. For the three plots shown, the burn rate was about 5.6 lb/h (2.5 kg/h) and the burn lasted about 1-1.5 hours. For clarity, only the CO profile is shown, although the HC profile is similar. As can be seen, the emissions tend to peak in magnitude near the beginning of the burn cycle as the stove is heating up. Following the initial surge, the emission level reduces to a lower, sustained level. This behavior is consistent with the findings of others (Kowalczyk et al. 1981; Knight 1982), where most of the emission occurs during the early stages of the burn cycle.

The temperature history is presented for two thermocouple positions: upstream of the secondary chamber and downstream of it. In the absence of secondary combustion, there is a temperature drop of 200 F-300 F (110 C-170 C) between these two positions. If the two temperature traces cross, and the downstream position is hotter than the upstream position, then secondary combustion must have occurred. If the two temperatures are close together, it is difficult to discern whether or not secondary combustion is occurring, because the effect may be masked by the heat loss from the secondary chamber. For purposes of this study, the existence of secondary combustion has been defined, somewhat arbitrarily, as whenever the temperature difference $[T_{upstream} - T_{downstream}] \leq 50$ F (28 C). By this definition, it can be seen that each of the three burns plotted in Figure 2 exhibit a short period of secondary burn during the initial stages.

Examination of runs 17.M and 33.M of Figure 2 reveals that the CO concentration appears to drop dramatically when secondary combustion occurs. However, the emissions eventually drop even if there is no secondary combustion. The importance of secondary combustion seems to be in reducing the magnitude and duration of the initial peak in emissions. If that is true, then only the initial stage of each burn, that critical for emissions, needs to be analyzed. Again for the purposes of this study, the critical stage of the burn cycle has been defined as the first one-third of the total elapsed time of the burn. All emission comparisons are based only on this critical stage. These two definitions, secondary burn and critical stage, are imporant to keep in mind as the various combinations of stove modification and burn rate are analyzed. For example, a first glance at Figure 2 might indicate that the addition of the ignitor alone offers some emission reduction and that the further addition of the regulated secondary air produces substantial emission cleanup. This proves to be not the case when critical stage emissions are averaged over all runs.

A compilation of the average results for all runs is given in Table 2; refer to Table 1 to determine the number of runs for each case. For the original, unmodified stove, the emissions decrease as the burn rate increases; this trend is well documented (Hartman and Rives 1985). The addition of the ignitor alone, employing naturally aspirated secondary air, reduces emission levels (the difference being statistically significant with 90% probability). By further adding the regulated flow of secondary air, however, the emissions increase to levels greater than the original stove yielded. Furthermore, the emissions seem to increase with burn rate. The introduction of the secondary air may have been quenching the secondary combustion, leading to the higher emission levels. However, the statistical significance of this difference is low (<50%) because of the wide variability in the emission measurements. Also worthy of note is the fact that the burn rate distinctions (high, medium, and low) were based on the damper setting and did not necessarily yield the same average wood consumption rate. For example, low burn rate tests for the original stove were at 4.2 lb/h (1.9 kg/h) while they were at 3.0 lb/h (1.4 kg/h) for tests with the ignitor.

The detailed results for each run are presented in Table 3. Recall that emissions are presented for only the first one-third of each burn cycle when hydrocarbon volatilization dominates. The percent of the time that secondary

combustion occurred is tabulated for this same time period. The most obvious feature of these data is the wide variations that arise; this phenomenon is fairly common in woodstove research. A scan of the results will reveal that the existence of secondary combustion is quite common for medium and high burn rates but rather uncommon for the low burn rate, regardless of the stove configuration. Even when secondary combustion did occur, its duration was usually brief and it did not necessarily cause a reduction in the emission.

CONCLUSIONS

This study sought to identify the conditions under which secondary combustion could be sustained in a dual-chamber woodstove. Besides the original stove, the additions of a electric ignitor and a regulated flow of secondary combustion air were tested. In general, neither of these additions promoted secondary combustion. Secondary combustion commonly occurred for medium and high firing rates, but it did not occur consistently at low burn rates. The reasons for the failure to sustain secondary combustion with the use of the ignitor are not clear. It may be possible to accomplish this task with different flow geometry, gas mixing, ignitor surface temperature, or some combination of factors. Examination of these possibilities was beyond the scope of this study.

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TABLE 1

Test Matrix with Number of Runs at Each Condition

Burn Rate	Original	Ignitor	Ignitor + Reg 2nd Air
Low Burn	7	5	9
Medium Burn	7	5	9
High Burn	7	4	9

TABLE 2

Average Emissions (with Standard Deviations) during the Initial Phase of Burn

Burn Rate	Original		Ignitor		Ignitor + Reg 2nd Air	
	CO%	HC%	CO%	HC%	CO%	HC%
Low Burn	.73 (.19)	.93 (1.47)	.56 (.17)	.06 (.06)	.82 (.35)	.14 (.07)
Medium Burn	.65 (.18)	.10 (.06)	.30 (.10)	.04 (.02)	.84 (.78)	.06 (.08)
High Burn	.48 (.08)	.08 (.02)	.14 (.04)	.02 (.01)	1.27 (.98)	.34 (.33)

TABLE 3

Data for All Burns

Stove Configuration	Run Number	Burn Rate (LB/HR)	Combustion		Average CO (PPM)			Average HC (PPM)		
			% Primary	% Secondary	Primary	Secondary	% Change	Primary	Secondary	% Change
	15.L	4.9	100	0	9034	0	0	5483	0	0
	16.L	4.0	100	0	7095	0	0	3288	0	0
	17.L	4.7	100	0	6196	0	0	1895	0	0
	18.L	5.1	100	0	3564	0	0	542	0	0
	19.L	3.6	100	0	9307	0	0	45055	0	0
	20.L	3.9	100	0	9096	0	0	7090	0	0
	21.L	3.2	100	0	7031	0	0	1836	0	0
	AVG	4.2	100	0	7332	0	0	9313	0	0
	15.M	7.4	36	64	3602	5475	52	299	448	50
	16.M	7.1	67	33	10552	7932	-25	2913	1016	-65
ORIGINAL	17.M	5.8	68	32	7668	6338	-18	960	495	-48
	18.M	4.9	52	48	4529	6241	38	495	507	2
	19.M	6.8	61	39	8615	5364	-19	1471	652	-56
	20.M	4.8	47	53	10736	6175	-42	2825	717	-75
	21.M	5.M	23	77	5801	4200	-28	1394	380	-73
	AVG	6.1	50	50	7075	5961	-6	1479	602	-38
	15.M	7.3	35	65	3247	5715	76	651	583	-10
	16.M	5.9	71	29	5849	6852	17	1000	876	-12
	17.M	6.6	56	44	4304	6912	61	456	694	52
	18.M	5.6	100	0	3564	0	0	542	0	0
	19.M	7.0	70	30	4632	5628	21	1225	803	-34
	20.M	6.5	92	8	4572	5363	17	883	629	-29
	21.M	7.2	50	50	5801	6287	8	1475	763	-48
	AVG	6.6	68	32	4567	5251	29	890	621	-12
	36.L	3.2	100	0	2586	0	0	281	0	0
	37.L	3.0	100	0	7086	0	0	1506	0	0
	38.L	2.8	100	0	5563	0	0	0	0	0
	39.L	2.9	76	24	6379	10232	60	0	0	0
	40.L	2.9	100	0	5686	0	0	1065	0	0
IGNITOR	AVG	3.0	95	5	5464	2046	12	570	0	0
	31.M	5.0	71	29	3212	5976	86	518	901	74
	32.M	4.6	100	0	1900	0	0	188	0	0
	33.M	5.6	63	37	3227	5890	83	514	647	26
	34.M	4.4	96	4	1853	9216	397	135	912	576
	35.M	4.0	100	0	4080	0	0	720	0	0
	AVG	4.7	86	14	2854	4216	113	414	491	135
	41.M	6.4	100	0	1269	0	0	208	0	0
	42.M	5.0	91	9	1305	3286	152	187	373	100
	43.M	4.2	100	0	892	0	0	80	0	0
	44.M	4.4	100	0	1499	0	0	134	0	0
	AVG	5.0	98	2	1341	822	38	152	93	25
	22.L	3.0	100	0	10080	0	0	1395	0	0
	23.L	3.8	58	42	8391	10165	21	1152	753	-35
	24.L	3.0	87	13	11426	8317	-27	1563	580	-63
	25.L	3.5	88	13	10872	9365	-14	2461	1144	-53
	26.L	4.6	31	69	7996	12935	62	3166	1364	-57
IGNITOR + REG 2nd AIR	27.L	3.8	100	0	5332	0	0	391	0	0
	28.L	3.4	100	0	1396	0	0	118	0	0
	29.L	4.1	92	8	13596	16546	22	1238	2151	74
	30.L	4.0	100	0	8333	0	0	2425	0	0
	AVG	3.7	84	16	8603	6370	7	1545	666	-15
	22.M	6.3	92	8	26261	13424	-49	2413	1451	-40
	23.M	5.1	37	63	1957	5530	183	28	147	423
	25.M	5.6	64	36	1909	3771	98	158	420	166
	26.M	5.1	31	69	4857	24708	409	130	1708	1210
	27.M	5.9	100	0	6450	0	0	227	0	0
	28.M	6.2	96	4	11717	4031	-66	691	410	-41
	29.M	4.5	100	0	2816	0	0	-43	0	0
	30.M	6.3	100	0	15626	0	0	1483	0	0
	AVG	5.6	77	23	8949	6432	72	641	516	214
	24.M	8.2	42	58	15074	12750	-15	831	631	-24
	22.M	5.7	96	4	850	1011	19	10064	57090	467
	23.M	6.2	29	71	19714	34096	73	1814	4452	145
	24.M	8.2	89	11	27336	4219	-85	2284	2435	7
	25.M	6.6	38	62	6779	18282	170	1009	1925	91
	26.M	9.5	56	44	20792	35808	72	1467	4870	232
	27.M	8.7	89	11	16307	10918	-33	1248	595	-52
	28.M	5.6	100	0	6773	0	0	253	0	0
	29.M	5.2	100	0	1236	0	0	0	0	0
	30.M	6.2	80	20	9961	14667	47	0	0	0
	AVG	7.0	72	28	12482	13175	25	1897	7200	87

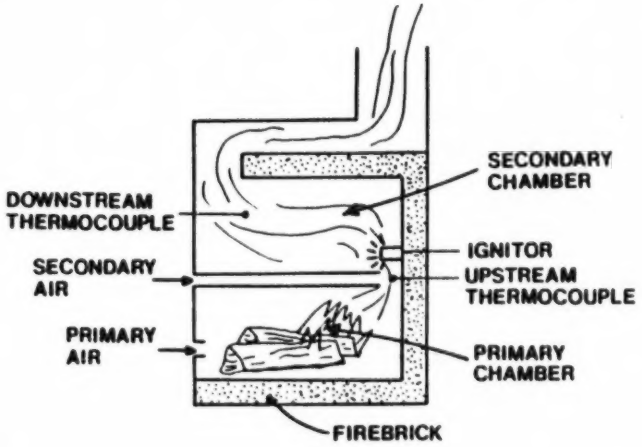

Figure 1 Woodstove schematic

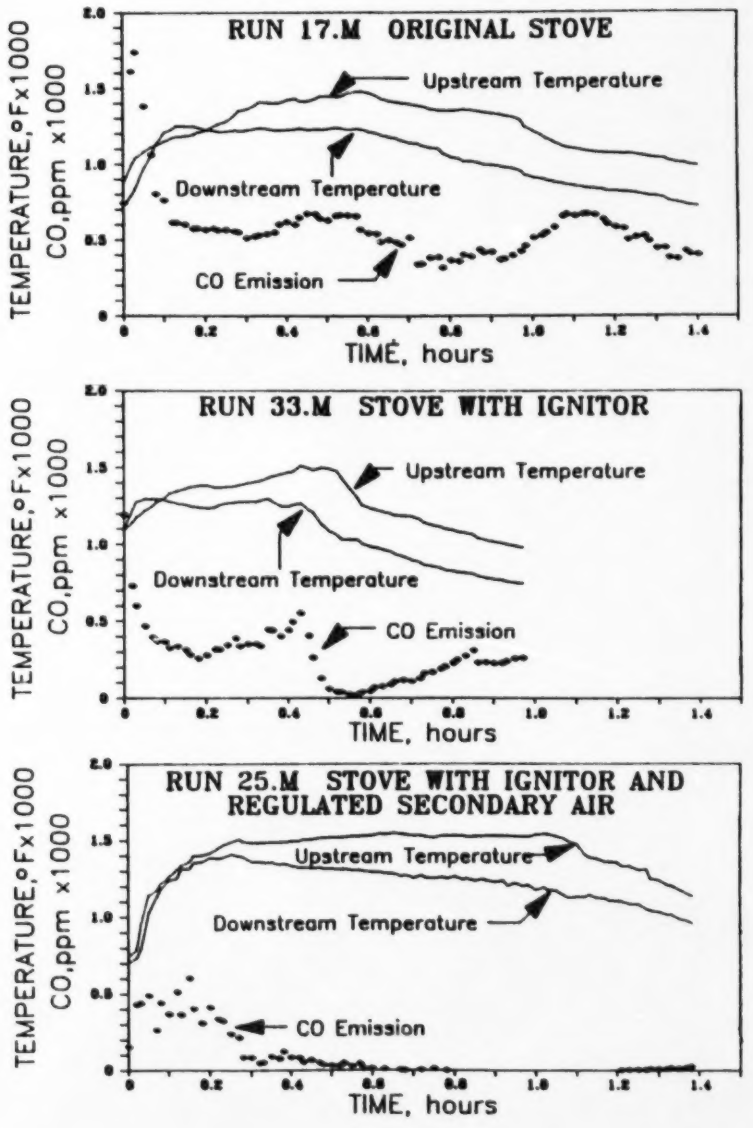

Figure 2 Typical histories of temperature and CO emission